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Investigation of aquifer plausible zones and their protective capacity using hydraulic parameters in Modomo/Kajola, Ile-Ife, Southwestern, Nigeria

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ABSTRACT

This study investigates aquifer plausible zones in Modomo/Kajola, Ile-Ife, using Dar Zarrouk parameters. The area, located in Universal Traverse Mercator (UTM) Zone 31N and characterized by pegmatite and granite gneiss in a Basement Complex terrain, spans between 830,000–830,500 mN and 663,000–664,000 mE. Twenty-eight Schlumberger-array vertical electrical soundings (VES) with AB/2 values from 1 to 155 m were performed using a Terrameter SAS 300C. The VES data, interpreted through partial curve matching and computer-assisted iteration, revealed three to five geo-electric layers: topsoil, lateritic/weathered layer, partly weathered basement, fractured basement, and fresh basement. The main aquifers comprise weathered materials (clay, sandy clay, clayey sand, and sand) and weathered/fractured basement, with aquifer thickness ranging from 3.3 m to 15.8 m (mean 9.9 m). Hydraulic properties indicate that longitudinal conductance varies from 0.00171 to 0.34848 mhos (mean 0.028467 Ω), hydraulic conductivity from 0.0000435 to 0.038079 m/day (mean 0.01858 m/day), and transmissivity from 0.00025 to 0.50456 m^2/day (mean 0.20158 m^2/day) while the GSLI ranges from 2 to 4 (mean 3). Overall, the area exhibits very low to medium aquifer potential, with the region around VES 7 favorable for groundwater abstraction.

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1. Introduction

The exploitation of aquifers is a global issue that has resulted in increased recognition of aquifer resources and sustainable management. Consequently, it is a necessity that an accurate and science-based approach is employed to utilising aquifer resources (Kwami et al. 2019; Ige et al. 2022; Mahmud et al. 2022; Mohammed et al. 2022).

Aquifer characteristics are effectively quantified through the estimation of aquifer hydraulic parameters such as porosity, permeability, hydraulic conductivity (K), transmissivity (T), aquifer depth, longitudinal conductance and transverse resistance. Hydraulic conductivity and transmissivity are essential properties relating to subsurface hydrology. They reflect the ease through which water moves in a geological formation (Yadav 1995; Szabo 2015; Kwami et al. 2019; Mohammed et al. 2022). Various methods are conventionally employed for determining aquifer hydraulic parameters such as obtaining core samples, carrying out laboratory tests and carrying out borehole pumping tests based on the boundary conditions of the aquifer. Kruseman and Ridder (1994) and Sattar et al. (2014) reported that a pumping test (at an existing borehole site) is a standard field method for determining hydraulic parameters. However, it is very expensive and time-consuming. The acquired parameters from the method characterise the well only in which the test is carried out. The estimated parameters cannot be extrapolated to cover the whole area due to the heterogeneity of geological formation. Moreso, hydraulic parameters vary intensely by orders of magnitude, even in the same aquifer (Mohammed etal. 2023). Conversely, in areas where there is inadequate hydrogeological data, surface geophysical methods such as the direct current electrical resistivity method can effectively be applied to characterise the aquifers by acquiring information about the geometry and hydraulic parameters (Ahmed et al. 1987; Khan et al. 2002; Mohammed 2020, 2020; Muhammad et al. 2022; Musaab et al. 2023). Vertical electrical sounding (VES) is a geophysical technique extensively applied to determine variation of electrical resistivities. It has been reported that VES is the most effective method for hydrogeological studies (Olaseeni et al. 2018; Oyeyemi et al. 2021; Stanly et al. 2021; Tepoule et al. 2022; Ige et al. 2022; Nugraha et al. 2022;

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Nwachukwu et al. 2022; Shah et al. 2022). The product of geophysical inversion of the measured apparent resistivity provides information about true layer thickness and resistivity.

True layer resistivities and thicknesses are used to compute layers longitudinal conductance and transverse resistance, which are known as Dar Zarrouk parameters. The parameters are used to determine aquifer hydraulic features (Maillet 1947; Niwas and Singhal 1981; Ezeh 2012; Ebong et al. 2014; Mohammed 2020; Mohammed et al. 2022; Musaab et al. 2023). Several studies, as extensively documented in the literature, have employed Dar Zarrouk parameters for aquifer characterisation (Utom et al. 2012; Kwami et al. 2019; Seli et al. 2021; Mahmud et al. 2022). Ako and Osundu (1986), following groundwater investigations in Darazo – a transitional zone within the Bauchi area – concluded that Dar Zarrouk parameters are closely related to borehole characteristics such as depth, lithology, porosity, permeability, hydraulic conductivity, transmissivity, aquifer thickness, and water-yielding capacity. The authors reported that zones with the maximum transverse resistance values relate with zones having the maximum water-yielding capacity. Ekwe and Opara (2012) characterised the water-yielding capacity of the Imo River Basin around Owerri and its environs using aquifer transmissivity generated from surface geoelectrical data. stated that Dar Zarrouk parameters are also used to identify the susceptibility of aquifers to surface and subsurface contamination. Evaluation of the susceptibility of aquifers to subsurface contamination defines the level of protective capacity of the overly unit above the aquifers. Oladapo and Akintorinwa (2007) described that the estimation of the protective capacity of aquifers aids in the detection of susceptible regions and the development of remediation schemes.

Modomo/Kajola is a quite developing community in the ancient town of Ile-Ife, Osun State. As a result of its closeness to two main tertiary institutions, Obafemi Awolowo University (OAU), Ile-Ife, and Oduduwa University, Ipetu-modu (OUI), the community is experiencing a fast rise in population and development (Oni et al. 2020). The growth in population and development of properties in the community was due to an increase in requests for accommodation by staff and students of these institutions and other residents. The increasing population density and subsequent increase in the water requirement of the community have also led many to explore alternative water sources as the public water supply is non-existent. Abuzied and Alrefaee (2017), Chirindja et al. (2017), and Oni et al. (2020) reported that the inhabitants of the community rely mostly on groundwater as a source of potable water supply. This is because groundwater sources can be developed near the location/site of need or demand, while the surface water is susceptible to pollution and very expensive to develop through a dam for even distribution.

Therefore, the main goal of this study is to determine the aquifer (hydrogeological) parameters, predict the protective capacity of the aquifer, and delineate the spatial distribution of the parameters in Modomo/Kajola community using the geo-electrical resistivity technique. This study intends to positively influence the exploitation and protection of aquifer resources in part of Modomo/Kajola community.

2. Description and geology of the study area

The study area is located approximately 4.2 km southwest of Obafemi Awolowo University (OAU) and 3.8 km east of the OUI campuses, within the interior of the old town of Ile-Ife, in the Ife Central Local Government Area of Osun State (Figure 1a). Geographically, it lies between latitudes 830,000 and 830,500 mN and longitudes 663,000 and 664,000 mE, within Universal Transverse Mercator (UTM) Zone 31N. The area, covering about 3.15 km^2, is home to a population exceeding 10,000 residents (Oni et al. 2020). The elevation ranges from 240 to 280 m above sea level (Figure 1b), featuring gently undulating topography in the eastern and southern parts, and gently sloping terrain in the western and northern parts. The climate is representative of the tropical hot zone of southwestern Nigeria. The wet season spans from April to October, with a mean annual rainfall of approximately 1,237 mm, while the dry season, characterised by little to no rainfall, lasts from November to March (Iloeje 1981). Geologically, the area lies within the Ife-Ilesha Schist Belt of the Precambrian Basement Complex in southwestern Nigeria. This Schist Belt comprises amphibolite, amphibole schists, pelitic schists, grey (banded) and granite gneisses, pegmatites, and dolerite dykes (Rahaman and Lancelot 1984; Turner 1989). The subsurface geology of the study area, shown in Figure 2, is predominantly composed of pegmatite and granite gneiss (Boesse 1989). Granite gneiss appears as low-lying outcrops with a medium to coarse-grained texture, while the pegmatite is typically overlain by a variably thick weathered layer. However, pegmatite veins are exposed along road cuts and erosion channels, particularly in the southwestern part of the study area. The soil profile – comprising clayey topsoil, laterite, a clayey weathered layer, a partly weathered/fractured basement, and fresh basement rock – is typical of the basement complex terrain in tropical climates), with chemical weathering being the dominant process. According to Olorunfemi and Fasuyi (1993), the principal aquifers in Basement Complex terrains are found within the weathered layer, as well as tectonically induced fractured and sheared zones.

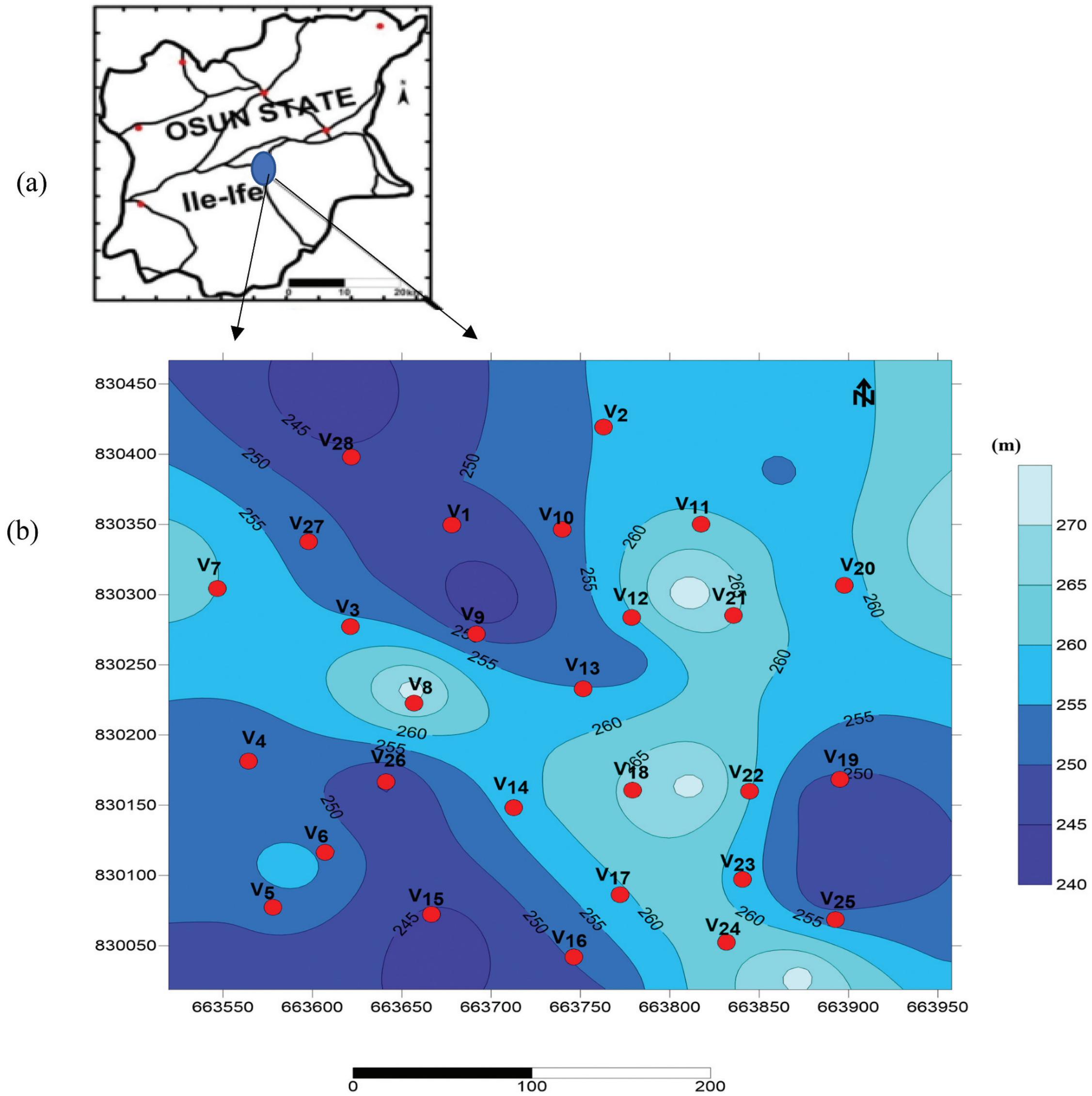

Figure 1. (a) Map of Osun state showing Ile-Ife and (b) topographical map of Modomo/Kajola showing VES points.

3. Materials and method

3.1. Vertical electrical sounding

A total of 28 Vertical Electrical Soundings (VES) were conducted across the study area (Figure 1) using the Schlumberger electrode array configuration. In this method, the current electrode spacing (C1 and C2), denoted as "AB", was progressively increased during data acquisition, while the potential electrode spacing (P1 and P2), denoted as "MN", remained relatively constant. During each measurement, electric current was injected into the subsurface through the current electrodes (C1 and C2), generating a potential difference between the potential electrodes (P1 and P2). The magnitude of this potential difference reflects the electrical resistance of the subsurface, which depends on both the electrode geometry and the electrical properties of the underlying materials The half-electrode spacing (AB/2) used in this study ranged from 1 to 155 m. The terrameter measured earth resistance values, which were then multiplied by a geometric factor specific to the electrode array used to obtain the apparent resistivity. The calculated resistivity values were manually plotted against half-electrode spacing (AB/2) on a bi-logarithmic graph sheet. The resulting curves were initially interpreted qualitatively through visual inspection to infer the nature of the subsurface layers. For quantitative interpretation, the smoothed curves were compared with master curves and standard charts (Orellana and Mooney 1966), followed by computer modelling using the WINRESIST software.

3.2. Aquifer hydraulic parameters

Dar Zarrouk parameters (longitudinal conductance (L) in Ω^{-1} and transverse resistance (T) in Ω m^2) are used to estimate aquifer hydraulic (or hydrogeological) parameters. These parameters are based on the equivalence between the flow of electric current and

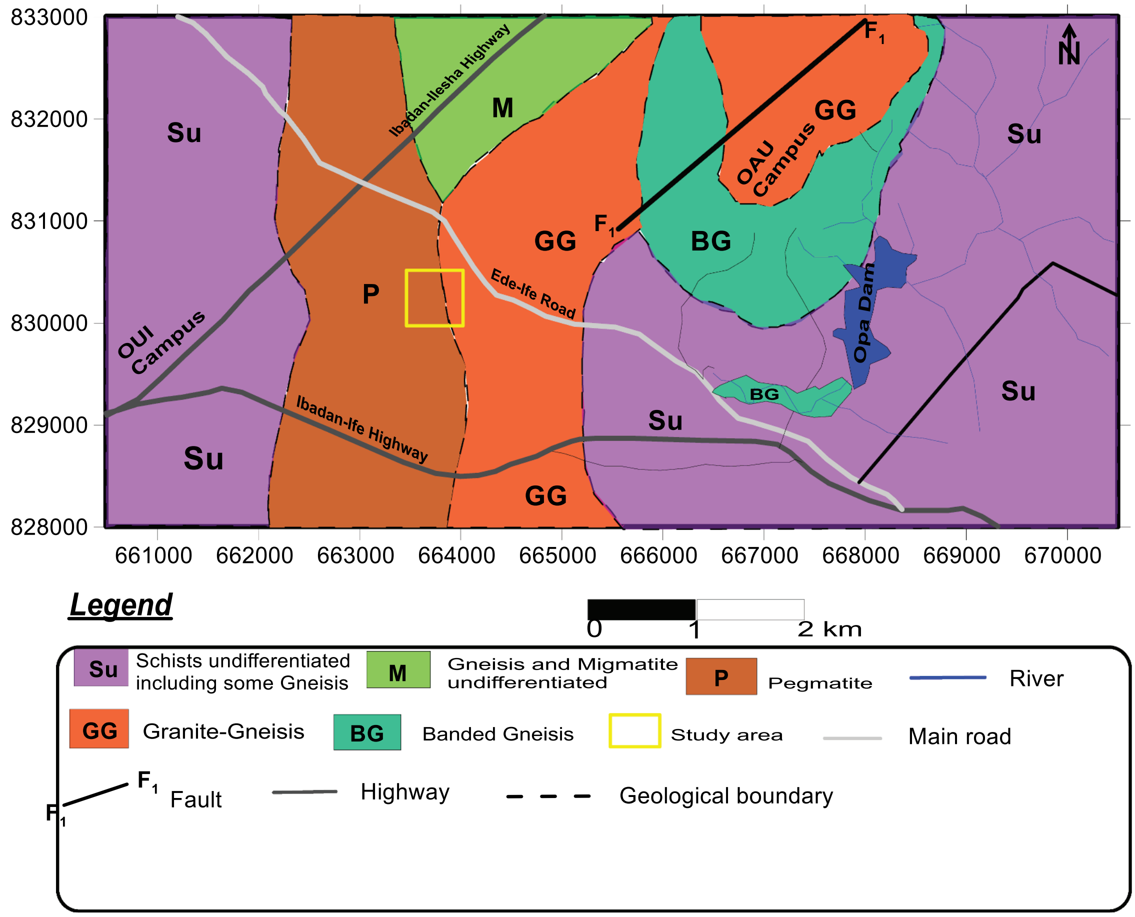

Figure 2. Geological map of part of Ile-Ife showing the study area.

groundwater aquifer. Dar Zarrouk parameters are the combination of geoelectrical parameters (layer thicknesses and true resistivity), which provides a simplified interpretation of the electrical models (Batte et al. 2010). These parameters are mathematically expressed as equations (1) and (2) as

$$L = {h_1}/{p_1} + {h_2}/{p_2} + {h_3}/{p_3} + \cdots + {h_n}/{p_n} = \sum_{i=1}^{n} \frac{h_i}{p_i} \quad (1)$$

$$T = h_1 * \rho_1 + h_2 * \rho_2 + h_3 * \rho_3 + \ldots + h_n * \rho_n = \sum_{i=1}^{n} h_i * \rho_i \quad (2)$$

where h, is layer thickness, ρ, is the true resistivity of the layer, and n, is the number of layers.

Oladapo and Akintorinwa (2007) suggested that the values of the total longitudinal conductance can be used to infer the vulnerability of groundwater aquifer or protective capacity. The protective capacity of the aquifer determines the ability of the geological column to impede the surface and subsurface pollutants. The maximum longitudinal conductance implies low vulnerability of aquifer to surface and subsurface pollution, thus high protective capacity, whereas low longitudinal conductance indicates the high vulnerability of aquifer to contaminants.

Considering the similarity between electric current flow (Ohm law) and groundwater flow (Darcy law), Niwas and Singhal (1981) proposed a relationship between Dar-Zarrouk and aquifer transmissivity (T_a) parameters theoretical equations in equations (3), (4) and (5):

$$T_a = K\sigma T \quad (3)$$

$$T_a = \frac{KL}{\sigma} \quad (4)$$

Transmissivity is the ease of movement of water through a whole thickness of an aquifer, whereas hydraulic conductivity is the rate of water moving through the unit width of the aquifer.

$$T_a = K * h_a \quad (5)$$

Where h_a is the aquifer thickness, K is the hydraulic conductivity, and σ is the electrical conductivity (reciprocal of electrical resistivity).

Based on the relationship between aquifer hydraulic conductivity and aquifer resistivities of granular materials, Odong (2013) suggested an empirical formula to determine the hydraulic conductivity (K) (equation (6)) as

$$K = 0.0538e^{-0.0072R_a} \quad (6)$$

where R_a is the resistivity of the aquiferous layer obtained from vertical electrical sounding.

3.3. Geoelectric layer susceptibility indexing (GLSI)

The GLSI is a hydrogeologic approach that gives the indices of the geoelectric parameters produced from VES for different lithological strata in the subsurface. It is an empirical idea presented to accompany other approaches to susceptibility evaluation (Oni et al. 2017). Contrary to the longitudinal conductance approach where the ratios of the geoelectric parameters (layer resistivity and thickness) are assigned indices, the GLSI assigns index to each geoelectric parameter (layer resistivity and thickness). GLSI is determined (Tables 1 and 2) with Equation 7.

$$GSLI = \frac{(\rho_{1r} + h_{1r}) + (\rho_{2r} + h_{2r}) + (\rho_{3r} + h_{3r}) + \cdots + (\rho_{nr} + h_{nr})}{2N} \quad (7)$$

where GLSI is the geoelectric layer susceptibility indexing, $\rho_{1\,r}$ is the resistivity of the first layer index rating, $h_{1\,r}$ is the thickness of the first layer index rating, $\rho_{2\,r}$ is the resistivity of the second layer index rating, $h_{2\,r}$ is the thickness of the second layer index rating, ρ_{nr} is the nth layer resistivity index rating, h_{nr} is the nth layer thickness index rating, and N is the number of geoelectric layers overlying the aquifer. The indexing deploys the MCDA (Multi Criteria Decision Analysis) method for parameters rating index. The assigned parameter indices are then normalised by dividing with the number of geoelectric layers (N) overlying the aquifer (Oni et al. 2017). .

4. Results and discussion

4.1. Geoelectric characteristics

Seven types curves with their percentage frequencies: H (42.8%), A and KH (17.9%), HKH and HA (7.1%), HKH and HA (7.1%) were observed within the study area and are suggestive that the subsurface is inhomogeneous (Table 3). The H, A, HA, AA and AAA are typical of the unfissured tropical climate soil profile (Acworth 1987; Adenika et al. 2018, 2024; Oni et al. 2020, and) whereas KH and HKH are indicative of tectonic-induced faulted/fractured subsurface sequence at a deep depth. A maximum of five lithological sequences were observed in the geoelectric section with different layer resistivity and thickness across each VES.

Across the geoelectric sections (Figure 3a–d) the first layer, topsoil composes of clay/sand, and have resistivity values varying from 49 Ω m to 484 Ω m, and thickness varying from 0.5 m to 1.5 m. The second layer is made up of clay, sand, or laterite. This layer is characterised by resistivity values that range from 34 Ω m to 708 Ω m with thicknesses ranging between 0.4 m and 5.3 m. The third layer, weathered layer is composed of clay, sandy clay, clayey sand and sand as observed by Oni et al. (2020), Adenika et al. (2024) and Falade et al. (2020). They are characterised by resistivity values between 86 Ω m and 989 Ω m and thickness between 3.9 m and 15.8 m. The layer thickness correlates nearly with the thickness observed by Oni et al. (2020) within the area. The fourth layer, fractured basements have resistivity values varying from 11 Ω m to 597 Ω m, and thickness varying from 1.5 m to 7.3 m while the fifth layer, fresh basement has resistivity values between 343 Ω m and 15,431 Ω m. Overburden thickness in the study area varies from 6.7 m to 18.4 m. Weathered layer and fractured basement are classified as fair to good aquifer potential zones in basement complex terrain (Olorunfemi and Fasuyi 1993). The geoelectric characteristics from previous studies in the area validate the results in this study (Table 4). In this study, the weathered/partly weathered layer and the fractured basement are identified as low to fair aquifer potential units.

Table 1. Geoelectric layer susceptibility index (GLSI) grading for resistivity parameters (Oni et al. 2017).

Resistivity range (Ω m)	Lithology	Susceptibility index grading
>401	Laterite	1
151–400	Lateritic sand	2
101–150	Sand	5
51–100	Clayey sand	3
21–50	Sandy clay	2
<20	Clay/silt	1

Table 2. Geoelectric layer susceptibility index (GLSI) grading for thickness (Oladapo et al. 2004; Oni et al. 2017).

Thickness (m)	Index point
>20	1
5–20	2
2–5	3
<2	4

4.2. Aquifer unit and thickness

The aquifer units within the study area are the weathered layer and fractured basement. The aquifer thickness varies from 3.3 m to 15.8 m with a mean value of 9.9 m (Table 5). Nwankwo and Ehirim (2010), Ezeh (2012) and Olorunfemi and Fasuyi (1993) reported that an aquifer with high thickness is a potential zone for groundwater exploitation, if it has sufficient porosity and permeability. Figure 4 reveals the variation in the aquifer thickness in the study area, and it is categorised in two regions. Dirty blue coloured region is characterised by thickness less than 10 m encompassing V4, V6, V12, V13, V14, V16, V17, V18, V19, V20, V21 and V22, which indicates low thickness. And the other (deep cream coloured) region is characterised by thickness

Table 3. Summary of VES interpretation.

VES	Layer	Resistivity Value $\rho(\Omega m)$	Thickness h (m)h	Overburden (m)	Curve type	Lithology description	Aquifer Units
1	1	265	0.7	15.6	HKH	Topsoil	(3)
	2	80	1.0			Weathered layer	(4)
	3	200	3.9			Partly weathered	
	4	104	10.0			Fractured basement	
	5	5744	–			Fresh basement	
2	1	213	0.8	16.6	H	Top soil	(2)
	2	98	15.8			Weather layer	
	3	701	–			Fresh basement	
3	1	351	0.6	11.6	H	Topsoil	(2)
	2	103	11.0			Weathered layer	
	3	679	–			Fresh basement	
4	1	98	1.2	11.7	A	Topsoil	(2)
	2	215	10.5			Weathered layer	
	3	2514	–			Fresh basement	
5	1	100	0.8	14.1	AA	Topsoil	(3)
	2	208	1.2			Lateritic layer	
	3	323	12.1			Weathered layer	
	4	15,431	–			Fresh basement	
6	1	56	0.7	16.9	KH	Topsoil	(3)
	2	169	1.0			Lateritic layer	
	3	96	15.2			Weathered layer	
	4	12155	–			Fresh basement	
7	1	151	0.5	18.4	HKH	Topsoil	(4)
	2	34	3.4			Weathered layer	
	3	87	4.3			Partly weathered	
	4	11	10.2			Fractured basement	
	5	343	–			Fresh basement	
8	1	150	0.8	12.0	H	Topsoil	(2)
	2	97	11.2			Weathered layer	
	3	453	–			Fresh basement	
9	1	257	0.6	13.6	H	Topsoil	(2)
	2	150	13.0			Weathered layer	
	3	1988	–			Fresh basement	
10	1	49	0.7	14.9	AAA	Topsoil	(4)
	2	97	0.4			Weathered layer	
	3	313	6.5			Partly weathered	
	4	597	7.3			Fractured basement	
	5	1778	–			Fresh basement	
11	1	75	0.9	16.2	KH	Topsoil	(3)
	2	251	5.3			Laterite	
	3	94	10.0			Weathered layer	
	4	5799	–			Fresh basement	
12	1	167	1.0	12.5	KH	Topsoil	(3)
	2	358	3.2			Lateritic layer	
	3	101	8.3			Weathered layer	
	4	731	–			Fresh basement	
13	1	398	1.2	12.0	H	Topsoil	(2)
	2	105	10.8			Weathered layer	
	3	2568	–			Fresh basement	
14	1	120	0.9	6.7	A	Topsoil	(2)
	2	989	5.8-			Weathered layer	
	3	2783				Fresh basement	
15	1	484	0.5	9.5	HA	Topsoil	(3)
	2	208	2.3			Weathered layer	
	3	534	7.0			Partly weathered	
	4	4800	–			Fresh basement	
16	1	178	0.7	14.3	KH	Topsoil	(3)
	2	555	3.2			Lateritic layer	
	3	125	10.4			Weathered layer	
	4	5934	–			Fresh basement	
17	1	228	0.8	10.3	H	Topsoil	(2)
	2	124	9.5			Weathered layer	
	3	1400	–			Fresh basement	
18	1	88	0.7	11.0	H	Topsoil	(2)
	2	72	10.3			Weathered layer	
	3	3008	–			Fresh basement	
19	1	220	1.0	7.0	HA	Topsoil	(3)
	2	100	2.0			Weathered layer	
	3	437	4.0			Partly weathered	
	4	801	–			Fresh basement	
20	1	150	0.7	9.2	A	Topsoil	(2)
	2	283	8.5			Weathered layer	
	3	1945	–			Fresh basement	
21	1	201	0.8	9.9	H	Topsoil	(2)
	2	140	9.1			Weathered layer	
	3	5147	–			Fresh basement	

(*Continued*)

Table 3. (Continued).

VES	Layer	Resistivity Value ρ(Ωm)	Thickness h (m)h	Overburden (m)	Curve type	Lithology description	Aquifer Units
22	1	345	0.5	14.6	KH	Topsoil	(3)
	2	471	2.0			Lateritic layer	
	3	109	11.1			Weathered layer	
	4	393	–			Fresh basement	
23	1	198	1.5	11.5	H	Topsoil	(2)
	2	98	10.0			Weathered layer	
	3	894	–			Fresh basement	
24	1	165	0.9	11.6	H	Topsoil	(2)
	2	89	10.7			Weathered layer	
	3	1907	–			Fresh basement	
25	1	168	1.0	8.1	A	Topsoil	(2)
	2	449	7.1			Weathered layer	
	3	2104	–			Fresh basement	
26	1	50	1.2	14.5	H	Topsoil	(2)
	2	48	13.3			Weathered layer	
	3	1814	–			Fresh basement	
27	1	148	1.0	13.0	H	Topsoil	(2)
	2	88	12.0			Weathered layer	
	3	1207	–			Fresh basement	
28	1	98	0.8	9.8	A	Topsoil	(2)
	2	321	9.0			Weathered layer	
	3	1989	–			Fresh basement	

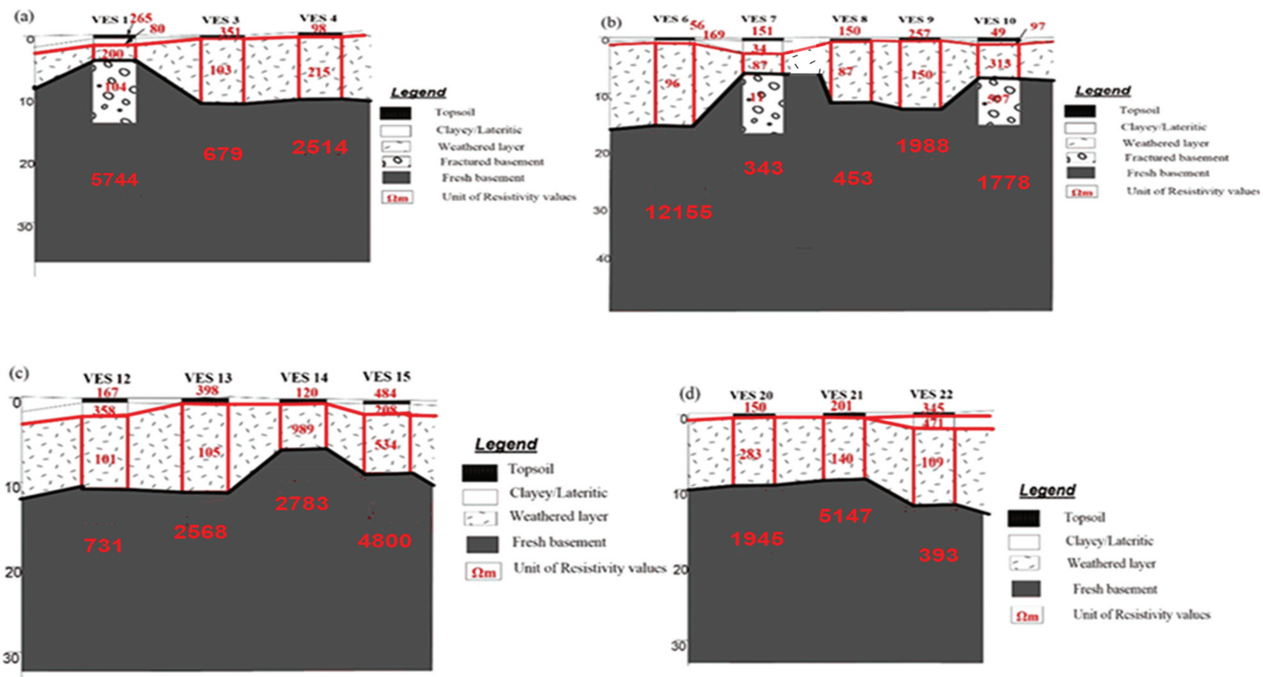

Figure 3. Typical geoelectric sections of the study area generated from VES interpretation results.

Table 4. Comparison of geoelectric characteristics of the study area and previous studies.

Lithological strata	VES – Electrical methods (This study)	VES – Electrical methods (Oni et al. 2020)	VES – Electrical methods (Falade et al. 2020)	Magnetic methods (Oni et al. 2020)
Topsoil thickness	49–484 Ω m 0.5–1.5 m	39–1050 Ω m 0.4–3.9 m	45–413 Ω m 0.8–1.7 m	Depth to magnetic basement (overburden) range from
Lateritic layer thickness	708 Ω m 5.3 m	—	469–1053 Ω m 0.4–1.4 m	↓
Weathered layer thickness	86–989 Ω m 3.9–15.8 m	32–964 Ω m 0.6–17.4 m	32–124 Ω m 3.0–11.8 m	↓
Partially weathered/ fractured basement thickness	11–597 Ω m 1.5–7.3 m	306–426 Ω m 13.2–24.5 m	202–1800 Ω m 1.5–61.1 m	↓
Overburden thickness	6.7–18.4 m	0 (outcrop) – 20.6 m	4.0–32.7 m	4.41–29.4 m

>10 m suggesting moderate thicknesses (V1, V2, V3, V7, V8, V9, V10, V11, V15, V23, V24, V25, V26, V27 and V28). With the average thickness value obtained, it implies that the study area generally has low aquifer thickness.

4.3. Aquifer hydraulic parameter

Dar Zarrouk parameters are used to determine aquifer hydraulic parameters such as hydraulic conductivity, transmissivity and longitudinal conductance from VES interpretation results. The aquifer hydraulic parameters of the study area are shown in Table 5.

4.3.1. Transmissivity and hydraulic conductivity

The transmissivity of the aquifer units in the study area was calculated, and the results were presented in Table 5. The values of transmissivity vary from 0.000252 m^2/day to 0.506456 m^2/day but are generally lower than 0.24000 m^2/day. Region with high transmissivity values is identified as region of high water-yielding potential, and aquifer materials are recognised to be fairly permeable to groundwater flow (Akintorinwa et al. 2020). The region with transmissivity value below 0.24000 m^2/day, between 0.24000 m^2/day and 0.33000 m^2/day and above 0.33000 m^2/day are characterised as very low aquifer, low aquifer and moderate potential respectively categorised by Adegboyega et al. (2024). It is observed that 54% and 32% of the VES points reveal very low and low aquifer potential, respectively, whereas 14% represent region with moderate potential, comprising V2, V6, V26 and V27 (Figure 5). The mean transmissivity value of the study area is 0.20158 m^2/day, thus indicating that the region is of low aquifer potential.

Figure 6 reveals the map showing the hydraulic conductivity in the study area while Figure 7 indicate the map of the study area showing variation in longitudinal conductance. The hydraulic conductivity values vary from 0.0000435 m/day to 0.03809 m/day with a mean value of 0.01859 m/day (Table 5). A zone with low hydraulic conductivity would be impermeable to fluid flow. George et al. (2015) suggested that the high variety of hydraulic conductivity of the aquifer may be as a result of the inhomogeneity nature of the aquifer, a condition accountable for extensive range in hydraulic conductivity. In the study, region with hydraulic conductivity values below 0.0200 m/day (V1, V2, V4, V5, V6, V9, V10, V11, V12, V13, V16, V19, V20, V21 and V22) suggests very low permeability. The region with hydraulic values greater than above the 0.0200 m/day (V3, V7, V8, V14, V15, V17, V18, V23, V24, V25, V26, V27 and V28) indicates low permeability. Consequently, the study area is mainly of low hydraulic conductivity. This implies that the entire region is impermeable to fluid movement because of the geologic control of the confined aquifer (complex) (Akintorinwa et al. 2020; Oni et al. 2020; Adegboyega et al. 2024).

4.4. Aquifer (vulnerability) protective capacity of the study area

The protective capacity (or vulnerability) of the aquifer units to pollutants was evaluated by examining the ability of the overlying layers to shield the main

Table 5. Aquifer parameters of the study area (Dar-Zarrouk parameter).

VES	Longitude	Latitude	ρ_a (Ω m)	h_a (m)	σ $(\Omega\ m)^{-1}$	L (Ω^{-1})	H (m)	K (m/day)	Ta (m^2/day)	GSLI
1	663609.6	830436.4	104	10	0.009615	0.0346	15.6	0.025444	0.254438	3
2	663787	830466.8	98	15.8	0.010204	0.00376	16.6	0.026567	0.41976	3
3	663579.2	830371.1	103	11	0.009709	0.00171	11.6	0.025628	0.281905	3
4	663682.4	830381.3	215	10.5	0.004651	0.0122	11.7	0.011442	0.120139	3
5	663763.1	830376.9	323	12.1	0.003096	0.01377	14.1	0.005258	0.063617	3
6	663862.4	830385.6	96	15.2	0.010417	0.01844	16.9	0.026952	0.409677	3
7	663519.6	830326.2	87	10.2	0.011494	0.15274	18.4	0.028757	0.293319	2
8	663620.2	830301.5	97	11.2	0.010309	0.00533	12	0.026759	0.299702	3
9	663694.3	830291.3	150	13	0.006667	0.00233	13.6	0.01827	0.237513	3
10	663809.4	830300	313	7.3	0.003195	0.03918	14.9	0.00565	0.041246	3
11	663876.9	830307.3	251	10	0.003984	0.03311	16.2	0.008829	0.088293	3
12	663957.7	830333.4	101	3.3	0.009901	0.01493	12.5	0.025999	0.085798	3
13	663655.9	830231.9	105	10.8	0.009524	0.00302	12	0.025261	0.272822	3
14	663779	830253.6	989	5.8	0.001011	0.0075	6.7	4.35E−05	0.000252	4
15	663547.4	830184	534	7	0.001873	0.0121	9.5	0.001151	0.008056	3
16	663641.4	830166.6	125	10.4	0.008	0.0097	14.3	0.021873	0.227484	3
17	663730	830150.7	124	9.5	0.008065	0.00351	10.3	0.022032	0.209299	4
18	663813.4	830163.7	72	10.3	0.013889	0.00795	11	0.032036	0.329975	3
19	663890.2	830159.4	437	4	0.002288	0.34848	7	0.002314	0.009255	3
20	663591.1	830105.7	283	8.5	0.003534	0.00467	9.2	0.007012	0.059605	4
21	663552.7	830057.8	140	9.1	0.007143	0.00398	9.9	0.019634	0.178671	3
22	663673.1	830057.8	109	11.1	0.009174	0.00613	14.6	0.024544	0.27244	3
23	663800.2	830075.2	98	10	0.010204	0.00758	11.5	0.026567	0.265671	3
24	663886.2	830085.4	89	10.7	0.011236	0.00545	11.6	0.028346	0.303298	3
25	663765	830018.7	449	7.1	0.002227	0.00595	8.1	0.002122	0.015068	3
26	663873	830030.3	48	13.3	0.020833	0.024	14.5	0.038079	0.506456	3
27	663952.4	830046.2	88	12	0.011364	0.00676	13	0.02855	0.342606	4
28	663884.9	830156.5	321	9	0.003115	0.00816	9.8	0.005334	0.048005	3

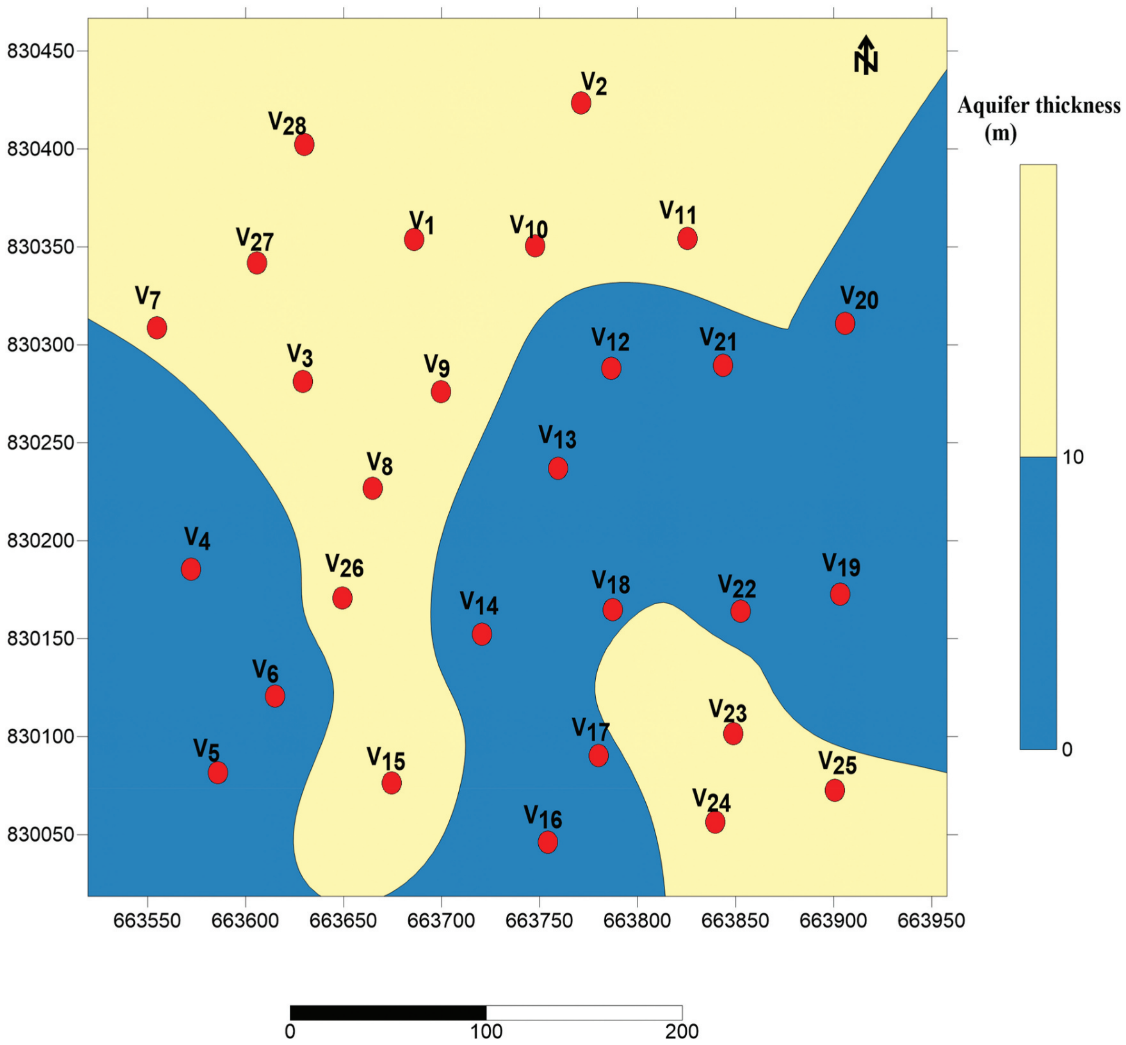

Figure 4. Map of the study area showing variation in aquifer thickness.

aquifers. This assessment was based on the results of longitudinal conductance and geoelectric layer susceptibility indexing (GLSI) of the overlying units.

4.4.1. Longitudinal conductance

Figure 6 illustrates the longitudinal conductance of the overlying unit (vadose zone) in the study area, which serves as an indicator of the protective capacity of the underlying aquifer units. The longitudinal conductance values range from 0.00171 Ω^{-1} to 0.34848 Ω^{-1}, with a mean value of 0.02847 Ω^{-1} across the study area. Highly permeable earth materials such as sand and gravel typically exhibit low longitudinal conductance due to their high resistivity, while impermeable materials like clay and shale show high longitudinal conductance values as a result of their low resistivity. Low longitudinal conductance is indicative of poor or weak protective capacity, whereas high conductance values are associated with good protective capacity (Oladapo and Akintorinwa 2007; Akintorinwa and Olowolafe 2013). Based on the classification in Appendix Table A1, the majority of the study area is characterised by low longitudinal conductance values (<1 Ω^{-1}), indicating weak to moderate protective capacity and suggesting that the underlying aquifers are vulnerable to contamination. Approximately 93% of the area falls within zones of low protective capacity. VES points V7 and V19 exhibit the highest longitudinal conductance values in the study area and are therefore classified as zones with moderate protective capacity (about 7%). Between the two, the V7 zone offers greater protection due to its thicker overlying layer (10.5 m) compared to V19 (7 m). Overall, the aquifers in the study area are considered vulnerable to potential infiltration of surface or subsurface pollutants (Akintorinwa et al. 2020; Adegboyega et al. 2024).

4.4.2. Geoelectric layer susceptibility indexing (GLSI)

The geoelectric layer susceptibility index (GLSI) for the study area was calculated and is presented in Table 4 and Appendix Table A3. Interpretation of the results was based on the classification in Appendix Table A2. Figure 8 illustrates the variation in both the GLSI values of the overlying lithology (vadose zone) and its thickness across the study area. The thickness of the vadose zone is critical in evaluating aquifer vulnerability to contamination, as a sufficiently thick vadose zone can retard the

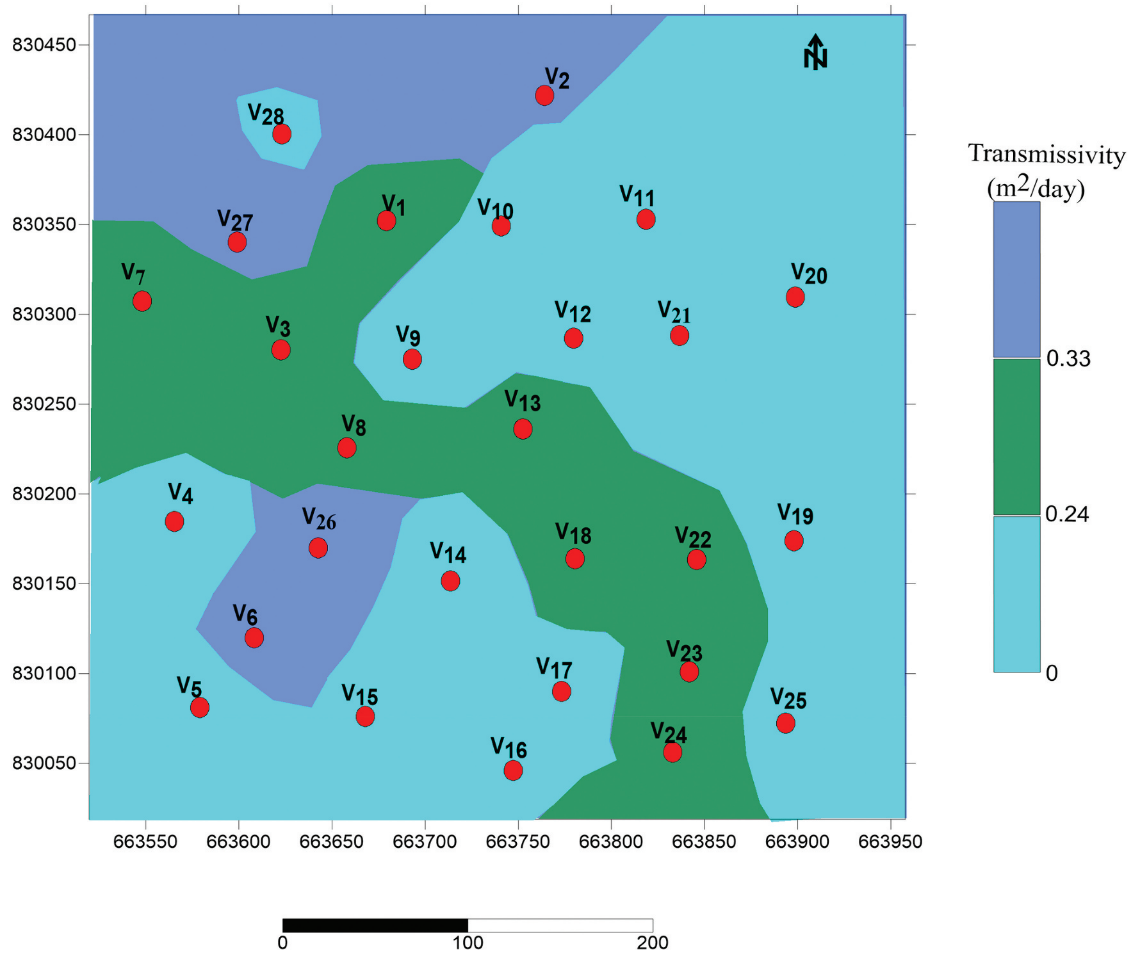

Figure 5. Map of the study area showing variation in transmissivity.

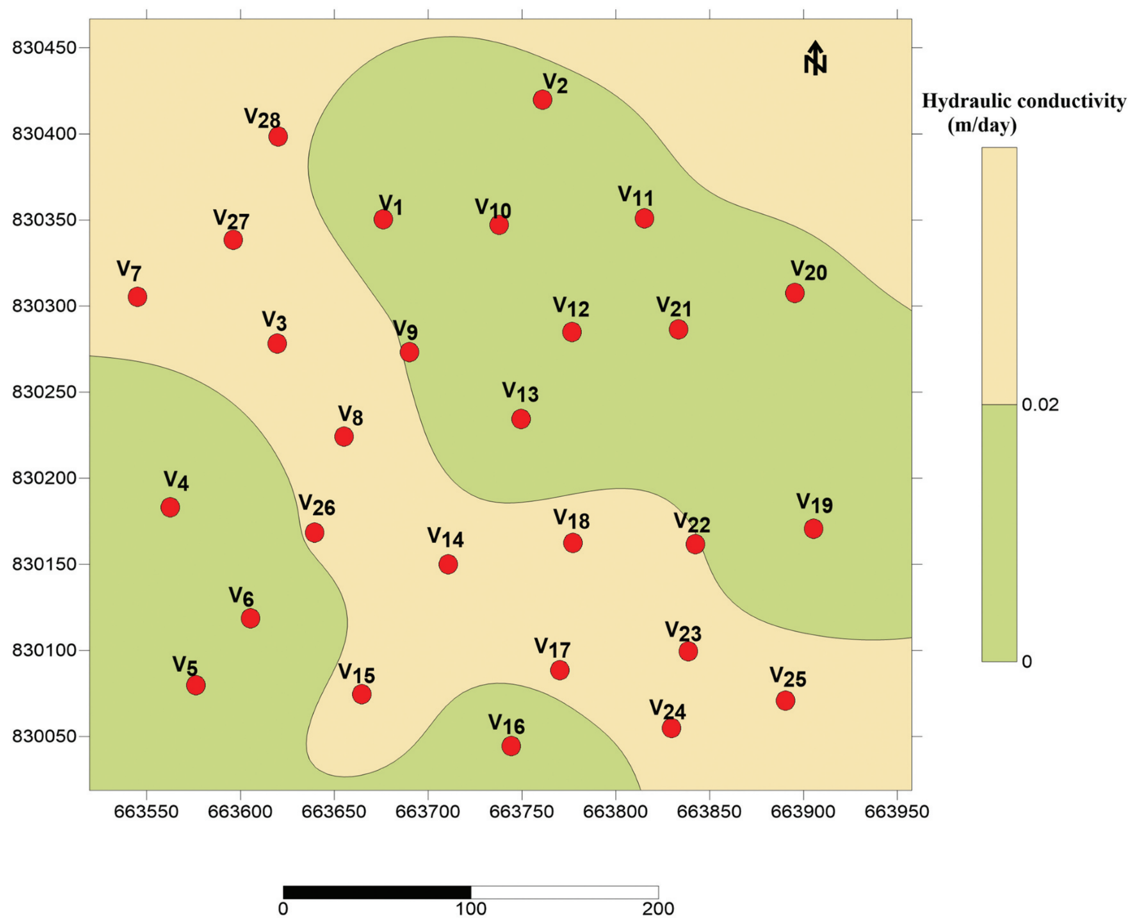

Figure 6. Map of the study area showing variation in hydraulic conductivity.

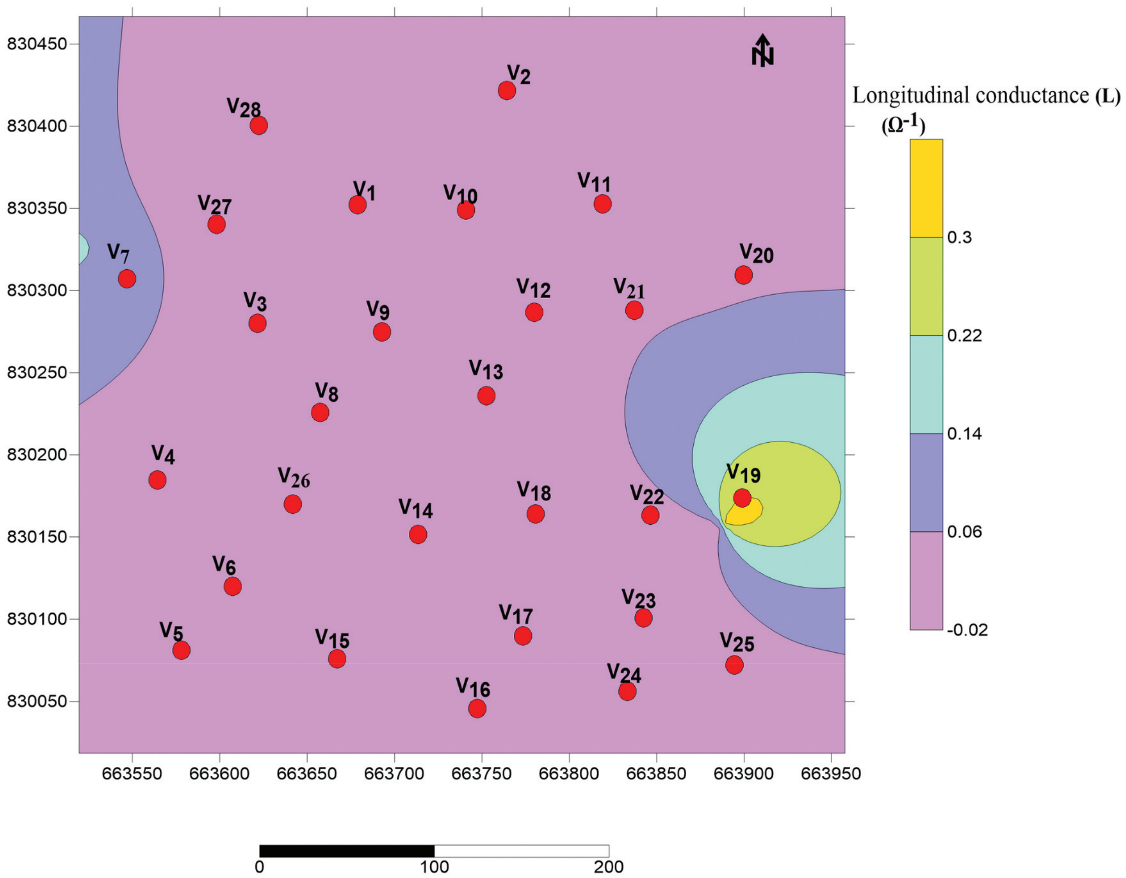

Figure 7. Map of the study area showing variation in longitudinal conductance.

movement of contaminants, allowing for degradation before they reach the aquifer. In the study area, GLSI values range from 2 to 4, with a mean value of 3, indicating generally high vulnerability (Oni et al. 2017). The GLSI map delineates three distinct zones: A blue-coloured region around V7, with a GLSI value of 2, indicates moderate vulnerability, a deep and light-yellow coloured region with values around 4 suggests extreme vulnerability, notably around V5, V6, V12, V13, V14, V15, V17 and V18 and the third region, characterised by a GLSI value of 3, signifies high vulnerability and includes locations V1, V2, V3, V9, V10, V11, V16, V19, V20, V21, V22, V23, V24, V25, V26, V27 and V28. Overall, the study area exhibits high vulnerability (i.e. low protective capacity) to contamination. The area around V7 shows moderate vulnerability, with a GLSI value of 2, consistent with findings from the longitudinal conductance map. Although V19 falls within the high vulnerability zone, the results from GLSI complement those obtained from longitudinal conductance estimations.

5. Conclusion

In this study, electrical resistivity survey, schlumberger vertical electrical sounding was carried to generate Dar Zarrouk parameters to investigate the aquifer plausible zones and their protective capacity in Modomo/Kajola Community, Ile-Ife, Osun State, Southwest, Nigeria. The VES data obtained from the study area were interpretated. The results showed that seven curve types were observed in the study area viz H, A, HA, KH, AA, AAA and HKH with the geoelectric layers ranging from three to five comprising of varying resistivity and thicknesses across each VES point. The geoelectric layers include the topsoil, lateritic/weathered layer, partly weathered basement, fractured basement and fresh basement. The geoelectric sections showing the main aquifers constitute weathered layer composed of clay, sandy clay, clayey sand and sand, and weathered/fractured basement (unconfined, semi-confined, and confined) with aquifer thickness varying from 3.3 m to 15.8 m and a mean value of 9.9 m.

The geoelectric parameters obtained were used to generate Dar Zarrouk parameters (aquifer's hydraulic conductivity, transmissivity, hydraulic conductivity and resistivity) and geoelectric layer susceptibility indexing (GLSI). Estimation and maps generated for transmissivity and hydraulic conductivity were used to assess and identify the aquifer plausible zones in the study area. Transmissivity map shows three regions with values: below 0.24000 m^2/day; between 0.24000 m^2/day and 0.33000 m^2/day, and above 0.33000 m^2/day are indicative of very low, low and moderate aquifer potentiality, respectively. Majority of the

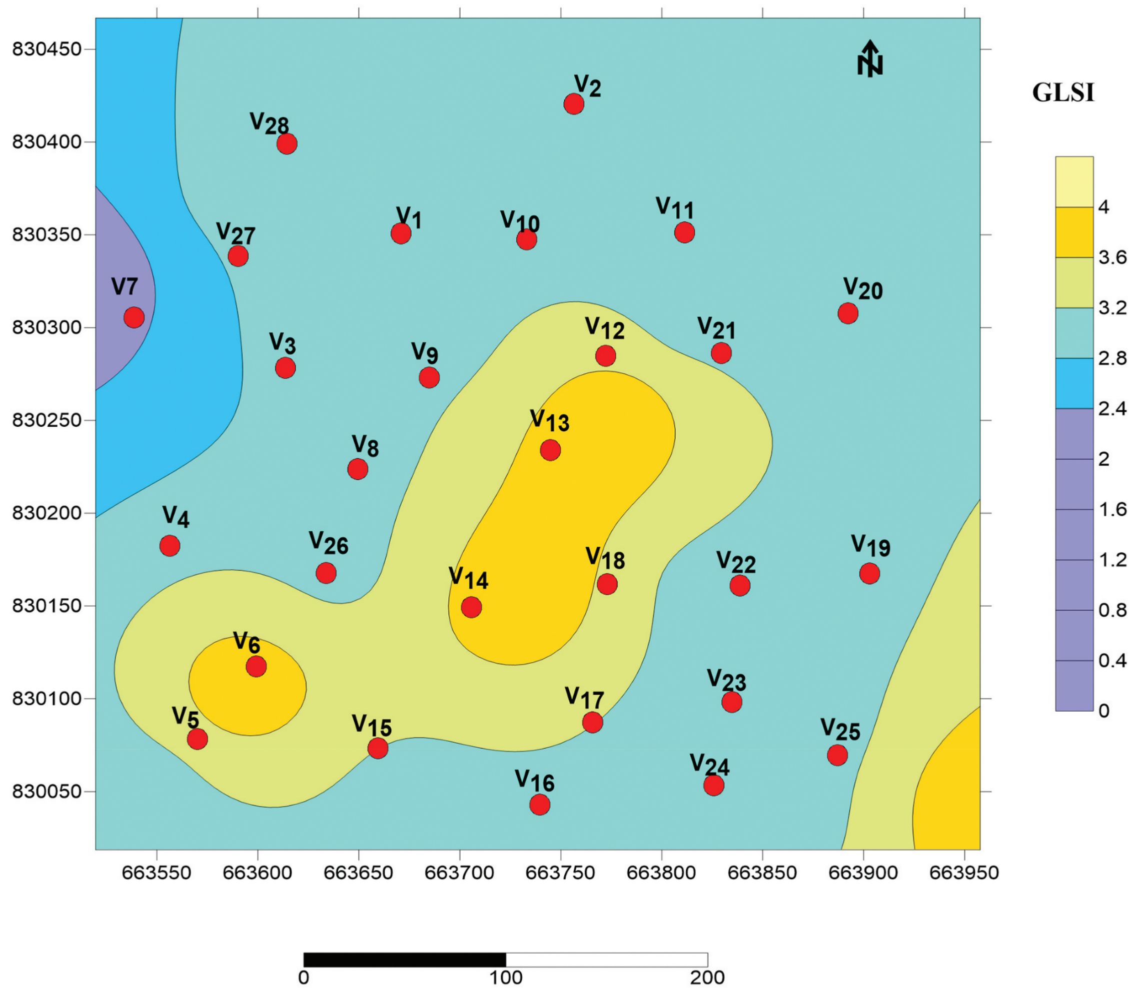

Figure 8. Map of the study area showing variation in geoelectric layer susceptibility indexing (GLSI).

VESs are at very low and low aquifer potentiality while region occupied with V2, V6, V26 and 27 exhibits moderate aquifer potentiality. The average transmissivity value of the study area is 0.20158 m^2/day, thus indicating low aquifer potential. Hydraulic conductivity map reveals values less than 0.0200 m/day indicating very low permeability in the study area, that is impermeable to fluid flow.

The longitudinal conductance values range from 0.00171 Ω^{-1} to 0.34848 Ω^{-1} with an average value of 0.02847 Ω^{-1} over the study area. Large parts of the study area, about 93% are characterised by low longitudinal conductance values, indicating weak to medium protective capacity (vulnerable to contaminants) for the underlying aquifers. V7 and V19 are observed to have the highest longitudinal conductance within the study area. The VESs may be classified as medium/moderately protective zones (7%) in the area. Thus, the underlying aquifers in the study area are vulnerable to potential infiltration of pollutants from the surface or within subsurface. GLSI map depicts that the entire region is characterised by high values which indicate high and extreme vulnerability to contaminants except portion around V7. The result complements LC maps. Therefore, the investigation reveals that the study area falls within (very low, low and medium) aquifer plausible and protective zones.

Region around V1, V2, V3, V6, V7, V26 and V27 can be developed for groundwater abstraction based on its hydrogeological characteristics. The aquifer potential map serves as an important tool for investors, town planners, estate developers, hydrologists and civil/building engineers, guiding decisions concerning the application of groundwater for local purposes whereas highlighting the demand for sustainable management practices in zones categorised by low groundwater potential.

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Appendix

Table A1. Rating of protective capacity of aquifers (Modified after Oladapo et al. 2004).

Longitudinal Conductance (Ω^{-1})	Protective Capacity Rating
>10	Excellence
1–10	Good
0.05–1	Moderate
<0.05	Weak

Table A2. GLSI parameters rating (Oladapo et al. 2004; Oni et al. 2017).

Vulnerability rating	Index
Low	1.0–1.99
Moderate	2.0–2.99
High	3.0–3.99
Extreme	4

Table A3. Protective capacity of the study area using GLSI parameters rating.

VES	Longitude	Latitude	GSLI	Vulnerability rating
1	663609.6	830436.4	3	High
2	663787	830466.8	3	High
3	663579.2	830371.1	3	High
4	663682.4	830381.3	3	Moderate
5	663763.1	830376.9	3	High
6	663862.4	830385.6	3	High
7	663519.6	830326.2	2	Moderate
8	663620.2	830301.5	3	High
9	663694.3	830291.3	3	High
10	663809.4	830300	3	High
11	663876.9	830307.3	3	High
12	663957.7	830333.4	3	High
13	663655.9	830231.9	3	High
14	663779	830253.6	4	Extreme
15	663547.4	830184	3	High
16	663641.4	830166.6	3	High
17	663730	830150.7	4	Extreme
18	663813.4	830163.7	3	High
19	663890.2	830159.4	3	High
20	663591.1	830105.7	4	Extreme
21	663552.7	830057.8	3	High
22	663673.1	830057.8	3	High
23	663800.2	830075.2	3	High
24	663886.2	830085.4	3	High
25	663765	830018.7	3	High
26	663873	830030.3	3	High
27	663952.4	830046.2	4	Extreme
28	663884.9	830156.5	3	High